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Azimuthal Angular Dependence of Atmospheric Muons at Sea Level

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Abstract

We report the azimuthal angular dependence of atmospheric muons at sea level. These muons are selected in the charge sign, the low momentum region between 2.5 and 20 GeV/c, and the zenith angular region 5°, 20°, 40°. The fluxes of positive and negative muons are affected by geomagnetic effect including the east-west effect and strongly related to four types of the atmospheric neutrino fluxes, ν_μ, $\bar{\nu_\mu}$, ν_e and $\bar{\nu_e}$ respectively.

1 Introduction:

Significant difference of neutrino fluxes between some underground experiments results(Hirata et al., 1988, Becker-Szendy et al., 1992, Fukuda et al.,1998) and calculations(Honda et al., 1995, Gaisser et al., 1988,1989, Lee & Koh, 1990) had been reported and this difference is considered the possibility of neutrino oscillations. More detailed calculations of atmospheric neutrino calculations have been demanded. However, Honda et al.(1995) point out that one of the difficulties in the calculation of atmospheric neutrino fluxes in the low energy is caused by the geomagnetic effects. Atmospheric neutrino in relation to the geomagnetic field are elucidate to measure the atmospheric muons in various azimuthal angles. These measurements provide the important information of the calculation of atmospheric neutrino fluxes. The measurements of each charge muon fluxes can also decide each neutrino fluxes, ν_μ, $\bar{\nu_\mu}$, ν_e and $\bar{\nu_e}$.

The Altazimuthal Counter Telescope with a Magnet Spectrometer, the OKAYAMA cosmic-ray telescope(located at altitude 34°41.2', longitude 133°55.4')(Yamashita et al., 1996) is suitable for the measurement of azimuthal angular dependence of muon fluxes at sea level, for next reasons.
1). It moves by a servomotor mechanism thus allowing any azimuthal and zenith angles to be used.
2). It measures the incoming directions, the momentum and the charge sign of incident cosmic-ray muon.

We report the results of differential positive and negative muon fluxes in each 45° azimuthal angle and in the zenith angle of 5°, 20°, 40°, in the momentum range from 2.5 GeV/c to 20.0 GeV/c. We also report the preliminary calculation of the minimum momentum with which muon can arrive at the earth for examination of our results.

2 Results:

The OKAYAMA cosmic-ray telescope has been in operation for some time and data for the analyses of the azimuthal angular dependence of muons at zenith angles of $5° \pm 5°$, $20° \pm 5°$ and $40° \pm 5°$ was accumulated in the observation period from 3 June 1997 to 12 May 1998. The effective observation times are 4333 h in the azimuth measurements. The total number of events is 854,732. The momentum region is between 2.5 GeV/c to 20 GeV/c.

The differential positive and negative muon fluxes in each 45° azimuthal angle at 5°, 20° and 40° zenith angles, in the Okayama University(altitude 34°41.2', longitude 133°55.4') are shown in Figure 1, 2 and 3 respectively. The momentum ranges of each line show 2.82 ± 0.33, 3.55 ± 0.41,

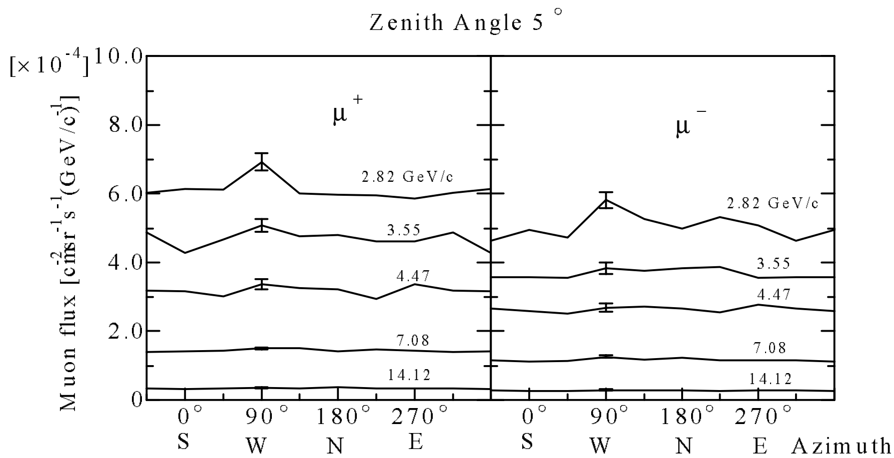

Figure 1: The azimuthal angular dependence of the absolute differential muon fluxes in the zenith angle of 5° for each momentum, 2.82, 3.55, 4.47, 7.08 and 14.12 GeV/c.

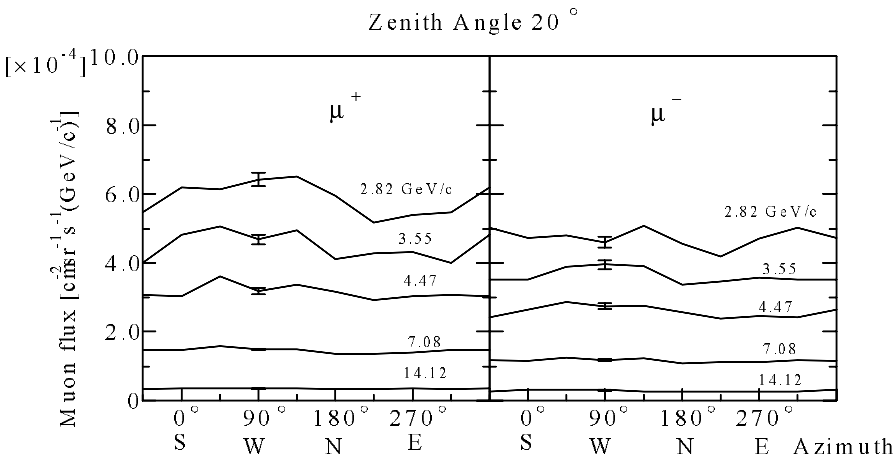

Figure 2: The azimuthal angular dependence of the absolute differential muon fluxes in the zenith angle of 20°.

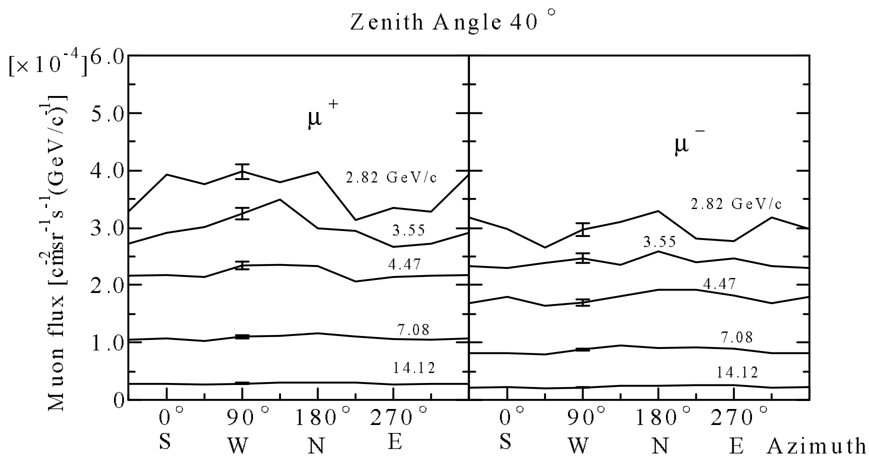

Figure 3: The azimuthal angular dependence of the absolute differential muon fluxes in the zenith angle of 40°.

4.47 ± 0.52, 7.08 ± 2.50 and 14.12 ± 5.00 GeV/c. The error bars show the statistical errors only. The reduction of positive and negative muon fluxes in the zenith angle 20° and 40° in the azimuthal angle near 270°, in the low momentum region is thought to be caused by the geomagnetic effect of primary protons.

3 The minimum momentum of atmospheric muons to arrive at the earth:

Our results are examined by the comparison with the calculations. First, we investigated the geomagnetic field effect. Low energy atmospheric muons are mainly produced following reactions,

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu_{\mu}}) \quad (1)$$

$$\mu^{\pm} \rightarrow \mathrm{e}^{\pm} + \nu_{\mathrm{e}}(\bar{\nu_{\mathrm{e}}}) + \bar{\nu_{\mu}}(\nu_{\mu}). \quad (2)$$

And π is produced by primary proton following equations,

$$\mathrm{P} + \mathrm{P(N)} \rightarrow \mathrm{P} + \mathrm{P(N)} + \pi^{+} + \pi^{-} + \pi^{+}.................. \quad (3)$$

These particles are affected by the geomagnetic field. The geomagnetic field determines the minimum momentum with which a cosmic ray can arrive at the earth. The minimum momentum per nucleon is defined as 'cutoff rigidity". However the cuttoff rigidity (=primary proton momentum) dose not concern the minimum muon momentum directly, since the energy loss in the atmosphere exists. We limit the reaction of a primary proton to following equations since the energy of a primary proton in relation to a π-on is the smallest and the proton is the most affected by the geomagnetic effects.

$$\mathrm{P} + \mathrm{P} \rightarrow \mathrm{P} + \mathrm{N} + \pi^{+} \quad (4)$$

$$\mathrm{P} + \mathrm{N} \rightarrow \mathrm{P} + \mathrm{P} + \pi^{-} \quad (5)$$

We calculate the muon minimum momentum to launch a test muon particle with a given momentum from our location(altitude 34°41.2', longitude 133°55.4'). The geomagnetic field is calculated using the report IAGA Division V Working Group 8(1995). The test particle are launched giving energy loss through the atmospheric and changing momentum depended on the geomagnetic field. At the distance near the tropopause where the atmospheric depth is 100 g/cm^2, test particle translate from a muon to a antiproton. When the test particle reaches a distance of 10 times the Earth's radius, the test particle is assumes to escape from the geomagnetic field and we define the first given momentum as the minimum momentum. The minimum momentum of atmospheric positive and negative muons at the zenith angle 40° are shown the solid lines in Figure 4 and 5. The dashed lines show the proton momenta translated from test muon momenta at the atmospheric depth 100 g/cm^2.

At azimuthal angle 270° and zenith angle 40°, the muon momenta to arrive at the earth are needed 3.0 GeV/c in the case of μ^{+}, 2.8 GeV/c in the case of μ^{-}, under the condition of reaction (4) and (5). These momentum limits reduce the muon fluxes in the low momentum region. These calculation results are consistent with the tendency of our experimental results.

We are going to proceed the calculations about the atmospheric muons.

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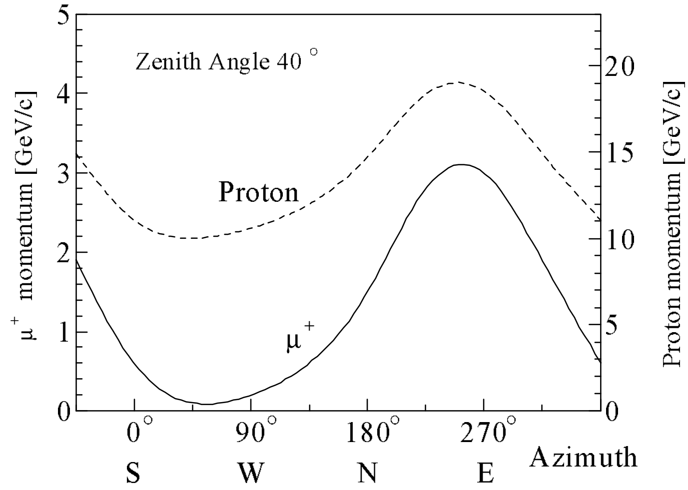

Figure 4: The minimum momentum of proton and μ^+ to arrive at the earth.
Solid line: The minimum momentum of μ^+. Dashed line: The minimum momentum of proton.

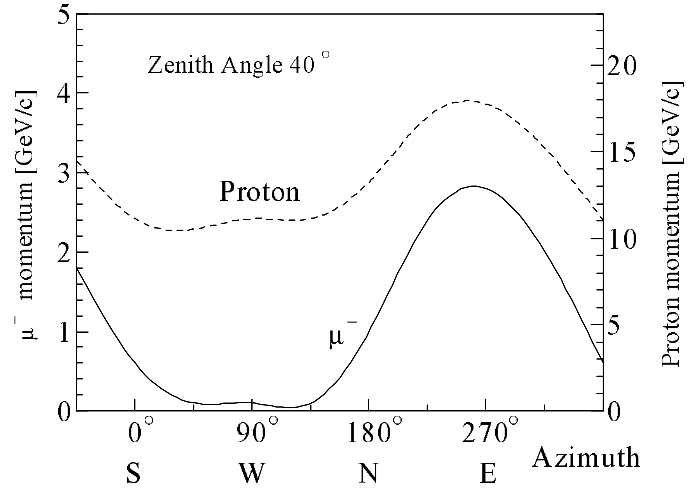

Figure 5: The minimum momentum of proton and μ^- to arrive at the earth.
Solid line: The minimum momentum of μ^-. Dashed line: The minimum momentum of proton.

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